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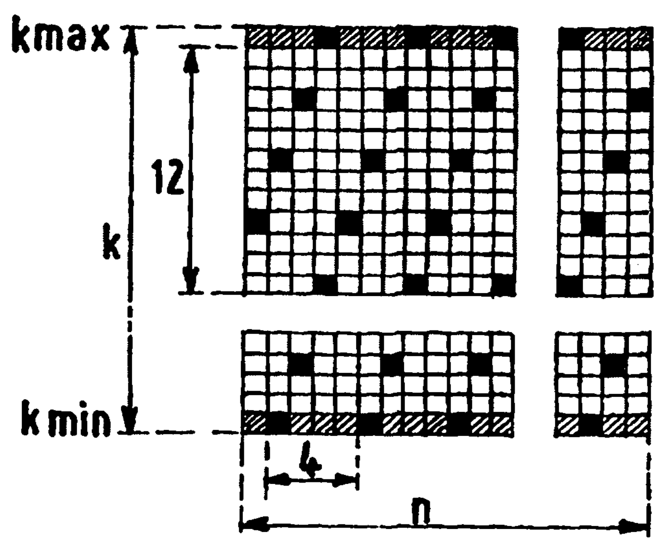
(54) Title: SYMBOL SYNCHRONISATION IN A MULTICARRIER RECEIVER

(57) Abstract

A receiver for multicarrier signals has means for synchronising to the sampling clock. The average phase variation of pilot signals is calculated for those subcarriers at the upper end of the spectrum; similarly, the average phase variation of the pilots at the lower end is calculated. The difference between these two averages, weighted by the frequency separation of the pilots, constitutes an error signal, which controls the frequency of the sampling clock.



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SYMBOL SYNCHRONISATION IN A MULTICARRIER RECEIVER

Description

FIELD OF THE INVENTION

The invention relates to a digital transmission system comprising a transmitter of multicarrier signals transmitted in frames, a part of the multicarriers transmitting pilot signals which are distributed in the frame in a pre-established order, and a receiver comprising:

- sampling means for sampling the received baseband-converted multicarrier signals with a sample clock,
- and synchronization means for synchronizing the sample clock.

The invention also relates to a receiver utilized in such a system and a method of attaining the synchronization.

The system may be utilized, for example, for transmitting digital television signals by a radio channel, more particularly, a disturbed channel called Rayleigh channel.

BACKGROUND OF THE INVENTION

For digital transmission systems, for ground-based broadcasting at high bit rates, the transmission channel can play an important role by producing intersymbol interference mainly due to multiple paths. This comes from echo phenomena the transmission channel is to process by complex equalizers in monocarrier transmission systems. An interesting solution to solve these echo problems consists of the use of a multicarrier transmission which implements multiplexed distribution of orthogonal frequency division carriers known as OFDM modulation (Orthogonal Frequency-Division Multiplexing). The OFDM technique thus consists of multiplexing the binary data on various orthogonal frequency carriers.

An OFDM signal is organized in frames, one frame comprising a sequence of OFDM symbols, one OFDM symbol being capable of transmitting data on each carrier or being capable of transmitting service signals, such as signals used for the automatic gain control, signals used for the synchronization (of frame, timing, radio frequency carrier), or used as reference signals for the differential modulation, or used for other functions. For

obtaining an estimate of the characteristics of the transmission channel, known data are inserted into each frame on specific carriers at given instants. These known data are notably pilot signals. The pilot signals appearing for a moment at given instants form the set of the distributed pilot signals. Certain carriers also transmit pilot signals which are continuously transmitted over the whole length of the frame. They form the set of pilot signals called "continuous".

A correct decoding of the transmitted data at the transmitting end calls for a correct synchronization of the receiver. In an OFDM system, various synchronizations are to be effected:

- a synchronization of the radio frequency carrier which converts the received radio frequency signal into a baseband OFDM signal;
- a synchronization for adjusting the window during which a Fourier transform operation is performed to demultiplex the OFDM carriers;
- a synchronization of the sampling frequency used for digitizing the baseband OFDM signal so as to avoid an offset of the window which permits of performing the Fourier transform.

The invention relates to the latter synchronization. This synchronization is mentioned in the document PCT WO 92/05646. This document indicates the possibility of considering the carrier phases received during a frame, any sampling frequency error having repercussions on the phases of the received carriers. None the less, whereas the synchronization of the sampling frequency is not considered necessary for the system described in that document, the result is that the manner for actually implementing such a technique is not revealed therein.

SUMMARY OF THE INVENTION

It is thus an object of the invention to describe means which permit of effecting a synchronization of the sampling frequency to effect the digitization of the OFDM signal in optimum fashion.

This object is achieved with a system and a receiver in which the synchronization means comprise a frequency detector which corrects frequency deviations of the sample clock by calculating a first average phase variation for the pilot signals appearing on the high-frequency carriers, and a second average phase variation for the pilot signals appearing on the low-frequency carriers, said frequency deviations being corrected in proportion to the difference of average phase variations which separates the first average phase variation from the second average phase variation in relation to a frequency gap

separating the high frequencies from the low frequencies.

The invention also relates to a sample clock synchronization method which comprises the following steps:

- calculation of a first average phase variation for the pilot signals appearing on high-frequency carriers,
- calculation of a second average phase variation for the pilot signals appearing on low-frequency carriers,
- calculation of an error signal for synchronizing the sample clock, the error signal being formed by a difference of average phase variations which separates the first average phase variation from the second average phase variation in relation to a frequency gap separating the high frequencies from the low frequencies.

The invention thus provides a rapid synchronization of the sampling frequency. The residual deviation of the sampling frequency resulting therefrom is reduced to a very small minimum depending on the characteristics of the loop used for the frequency alignment. The system is very well adapted to operating with Rayleigh channels.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

Fig. 1 shows a general diagram of a digital transmission system;

Fig. 2 shows a diagram of a receiver comprising a sampling frequency detector according to the invention;

Fig. 3 gives a representation of an example of a composition of certain OFDM symbols in a frame;

Fig. 4 shows a curve representing the average phase variations of the pilot signals plotted against the value of the carrier frequency; and

Fig. 5 shows a curve representing the standardized residual deviation of the sampling frequency plotted against the number of symbols used for attaining the synchronization.

DESCRIPTION OF EMBODIMENTS

For a better understanding of the invention, let us first consider how the signals are formed at the transmitting end.

The OFDM technique consists of frequency multiplexing various orthogonal carriers modulated by transmit signals. These signals are generally the result of coded digital modulations such as, for example, QAM, QPSK and other modulations. An OFDM symbol s(t) may be written as:

$$1)\quad s(t) = R_e\{ e^{2i\pi f_0 t} \sum_{k=0}^{N-1} x_k.\phi_k(t)\}$$

for $j.T' < t < (j+1)T'$

with $\phi_k(t) = e^{2i\pi kt/T'}$ *for* $jT' \leq k \leq (j+1)T'$

where:

T' : total duration of an OFDM symbol, $T'=T+T_G=(1+\Delta)T$;

R_e: real part of a complex number;

k : index of the orthogonal carriers;

T: useful duration of an OFDM symbol;

T_G : duration of the guard interval;

Δ : proportion of the guard interval in relation to the useful duration of a symbol $\Delta = \frac{T_G}{T}$.

N: number of useful samples of an OFDM symbol and also maximum number of carriers.

N_G: number of samples of the guard interval.

j : index of the OFDM symbol in the frame;

f_0: frequency of the first carrier.

To avoid the problem of spectrum overlap and to facilitate the filtering at the receiving end, the sum corresponding to equation (1) is made of N_u carriers, where N_u is the number of useful carriers ($N_u < N$).

An OFDM symbol formed by N_u complex symbols x_k resulting from a QAM, QPSK or other modulation appears between the instants j.T' and (j+1)T'. Each symbol x_k modulates an orthogonal carrier with $0 \leq k \leq N-1$.

The main role for the guard interval is to absorb the echoes of the previous symbol coming from the multipath channel and for which the delays are less than

T_G. During the guard interval, a signal is transmitted copied from a part of the useful signal.

For the following of the description, the term "symbol" will be used to designate the actual OFDM symbols. The symbols x_k (coming from a QAM, QPSK or other modulation) which modulate a given carrier at a given instant will be designated by the term "cell", an OFDM frame thus being formed by OFDM cells frequency-divided over all the carriers and over the entire length of the frame.

Fig. 1 diagrammatically shows the means used at the transmitting end for effecting the OFDM modulation, that is to say, for forming the signal s(t) of the equation (1), and the means used at the receiving end. A data source DATA 11 delivers the data x_k of the QAM type or other types, to an OFDM modulator 13. For distributing the data over various carriers, the modulator preferably comprises a calculating device 51 for calculating an inverse fast Fourier transform FFT^{-1}. The device 51 is preceded by a multiplexer MUX 52 which also has an input 53 used to insert control signals intended for controlling the transmission (channel estimation, synchronization, service signals, etc.). The multiplexer 52 is followed by a deserializer 55. For obtaining the inverse Fourier transform, the device 51 has a number $N = 2^x$ inputs where x is an integer. A serializer P/S 54 delivers a digitized OFDM signal s_k formed by N_G time-division samples which correspond to the guard interval, and formed by N time-division samples for the useful duration of each OFDM symbol. The output of the modulator 13 is connected to a radio frequency modulator 15 which conveys the modulated signals s(t) to the transmission channel.

At the receiving end, the received signal r(t) is transformed into a baseband signal $r_B(t)$ in a radio frequency demodulator RF TUNER 115. The baseband signal is then processed by an OFDM demodulator 113. The synchronization means are not shown in Fig. 1. The signal $r_B(t)$ is first of all digitized in a digitizer 30. The digitized signal r_B is then transformed in parallel in a deserializer S/P 154, which eliminates the N_G time-division samples in the guard interval and which deserializes the N time-division samples of the useful duration of the OFDM symbol. The data then enter a device FFT 151 which performs a Fourier transformation. The data then enter a deserializer P/S 155 and then a demultiplexer DEMUX 152 which removes from each OFDM symbol the control signals 153 which do not contain the actual data. The symbols R_k coming from the demodulator 113 are then decoded in a decoder DEC 111 for recovering the QAM (or QPSK or other modulation) symbols x_k.

The symbols on the output of the modulator 13 are transmitted in frames. Thus, one frame gathers various time-division multiplex OFDM symbols. The cells of an OFDM symbol enclose for the greater part data, but certain cells contain particular signals,

for example, pilot signals, or particular signals used for synchronization (of frame, timing, carrier) purposes, or used as a reference symbol of the differential modulation.

In the course of a frame duration, a carrier will be capable of, for example, transmitting the following data structure:

1	2	3	4	5	6	j-1	j	125
PILOT	*DATA*	*DATA*	*PILOT*	*DATA*	*DATA*	....	*PILOT*	.... *DATA*

For a frame containing, for example, 125 symbols, having a symbol duration T' = 160 μs, the duration of the frame is 20 ms. The symbol PILOT is a known symbol for the receiver. The symbol is used for estimating the characteristics of the transmission channel so as to decode the data correctly. During a frame, certain carriers transmit a given pilot (PILOT) several times. Nevertheless, the multicarriers are provided for transmitting for the major part data x_k (DATA).

The invention uses the regular repetition of the pilot signals for synchronizing the sample clock. Fig. 3 shows a frame part where an example of a composition of the OFDM symbols appears. In the vertical direction of the raster is indicated the sequence of carriers having index k, the carrier having the lowest frequency having index k_{min} and the carrier having the highest frequency having the index k_{max}. In horizontal direction is indicated the number of the OFDM symbol in the frame. An OFDM symbol is thus represented by a column of the raster. A carrier is represented by a row of the raster. A raster element is a cell that contains a data or a pilot signal or a service signal. The pilot signals are, for example, pilot frequencies. For simplicity, only the data and the pilot signals are shown in Fig. 3. The black cells represent the pilot signals transmitted with much power. The grey cells represent the pilot signals transmitted with reduced power. The carrier having the lowest frequency and the carrier having the highest frequency continuously transmit only pilot signals. For the other carriers, the pilot signals are distributed regularly, for example, with one step in 4 in horizontal direction (time) and one step in 12 in vertical direction (frequency).

The frequency detector according to the invention utilizes the phase variations of the pilot signals which are different depending on whether the carrier frequency is high or low. These phase variations are due to the drift of the FFT window in the course of time, notably when the sampling frequency is not synchronized correctly. Let f_s = N/T be the theoretical sampling frequency. By spreading the data to be transmitted over N carriers,

the carrier frequencies are determined by $f_k=\frac{f_s}{N}.k$, where k is a number comprised between 1 and N. Let τ_d be the time-division drift of the FFT window between two symbols, then the drift is due to a sampling frequency error equal to δf_s. The drift τ_d is thus so that:

$$(1) \quad \tau_d = (N+N_G)\frac{\delta f_s}{f_s(f_s+\delta f_s)} \approx (1+\frac{N_G}{N})N\frac{\delta f_s}{f_s^2}.$$

Let $H_n(f)$ be the transfer function of the channel at the time nT'. The transfer function $H_n(f)$ results from the following recurrent relation:

$$(2) \quad H_n(f) = H_{n-1}(f)\, e^{-2j\pi f\tau_d}$$

where the term $e^{-2\pi f\tau_d}$ represents the time-division offset due to the drift τ_d. The frequency response of the channel having frequency f_k is thus:

$$(3) \quad H_{n,k} = H_n(k\frac{f_s}{N}) = H_{n-1,k}\, e^{-2j\pi k(1+\frac{N_G}{N})\frac{\delta f_s}{f_s}},$$

(k is the index of the carriers and n is the number of a cell in the frame).

The phase variation $\delta_p\phi_{n,k}$ between the symbols n and n-p is written as (p integer):

$$(4) \quad \delta_p\phi_{n,k} = arg(H_{n,k})-arg(H_{n-p,k}) = arg(H_{n,k}\, H^*_{n-p,k})$$

that is:

$$(5) \quad \delta_p\phi_{n,k} = -2\pi kp(1+\frac{N_G}{N})\frac{\delta f_s}{f_s}.$$

Let C_p be the set of (n,k) cells belonging to the set of pilot frequency cells called continuous cells and let S_p be the set of the (n,k) cells belonging to the set of pilot frequency cells called dispersed cells.

For the cells belonging to the set C_p, between two adjacent cells, one has approximately:

(6) $\delta_1\phi_{n,k} \simeq arg(R_{n,k}\, R^*_{n-1,k})$,

where $R_{n,k}$ is the received data (symbol n on the carrier k):

(7) $R_{n,k} = x_{n,k}\, H_{n,k} + \xi$

where ξ is a variable noise level.

For the cells belonging to the set S_p, between two cells which are p=4 cells apart, one has approximately:

(8) $\delta_4\phi_{n,k} \simeq arg(R_{n,k}\, R^*_{n-4,k})$.

An estimate of the sampling frequency error may be obtained by measuring the difference between, on the one hand, a first weighted average, measured according to the phase variations relating to the pilot frequencies appearing on the carriers which have high carrier frequencies and, on the other hand, a second weighted average, measured according to the phase variations relating to the pilot frequencies appearing on the carriers having the low carrier frequencies.

An approximation of the first weighted average phase variation is such that:

(9) $$\delta\phi_+(n) \simeq \frac{\Sigma_{(n,k)\in S_p^+} Im(R_{n,k}\, R^*_{n-4,k})}{\Sigma_{(n,k)\in S_p^+} Re(R_{n,k}\, R^*_{n-4,k})}.$$

An approximation of the second weighted average phase variation is such that:

(10) $$\delta\phi_-(n) \simeq \frac{\Sigma_{(n,k)\in S_p^-} Im(R_{n,k}\, R^*_{n-4,k})}{\Sigma_{(n,k)\in S_p^-} Re(R_{n,k}\, R^*_{n-4,k})}$$

The estimate of the sampling frequency error is then:

(11) $$\frac{\delta\hat{f}_s}{f_s} = \frac{\delta\phi_+(n) - \delta\phi_-(n)}{8\pi(k^+ - k^-)(1+\frac{N_G}{N})}.$$

In these equations, the sub-set S_p^+ is a sub-set of S_p corresponding to the

high pilot frequencies which have an average index k^+. Similarly, the sub-set S^-_p is a sub-set of S_p corresponding to the low pilot frequencies which have an average index k^-.

The difference $\delta\phi_+ - \delta\phi_-$ makes it possible to get rid of the common phase noise.

Fig. 4 shows the phase variations of the pilot frequencies plotted against the index k of the carriers. By measuring the average phase variations $\delta\phi_+$ *et* $\delta\phi_-$, according to the invention it is possible to form an error signal for synchronizing the sampling frequency.

Fig. 2 shows a diagram of the receiver according to the invention. The baseband signal $r_B(t)$ is sampled in the digitizer 30. The sampled signal r_B enters a transforming device 31 which transforms the real data r_B into analytic complex data (I,Q). Thereafter, a deserializer S/P 154 eliminates the N_G complex time-division data which correspond to the guard interval and produces the N complex data of the useful interval in parallel. They enter the Fourier transforming device 151 which produces the received R_k symbols in parallel. The data then enter a serializer P/S 155 and then a demultiplexer 152 which removes the signals which are no data to deliver the symbols R_k without control signals.

For synchronizing the sample clock H_s, the receiver comprises a loop 1. The demultiplexer 152 comprises a pilot frequency retriever 32 which determines the instant at which the pilot frequencies appear in the frame. The pilot frequencies thus detected are applied (connection 153a) to a frequency detector 33 SAMPL DET which calculates the error signal $\frac{\delta f_s}{f_s}$. Therefore, it performs the calculations which correspond to the equations 6 and 8 to 11. Each new estimate of the error signal is formed with the OFDM symbol frequency. This permits of diminishing the lock-on time of the system and reducing the residual sampling frequency jitter. The frequency detector may be, for example, a signal processing device or a microcomputer. After being filtered in a loop filter 34, the error signal triggers the clock generator VCXO 35 which applies the sample clock H_s to the converter 30.

The frequency detector 33 is a fine detector that is active when the offset δf of the carrier frequency occurring in the tuner 115 and also the sampling frequency errors are small. In practice, one establishes limits defined by, for example:

$$\delta f.T' < 0{,}125 \quad \wedge \quad \delta f_s.2p\pi(k^+ - k^-)\ \frac{T'}{N} < 0.75.$$

In the absence of noise, these limits may be exceeded up to the theoretical limits defined by:

$$\delta f.T' < 0{,}25 \quad \wedge \quad \delta f_s.2p\pi(k^+ - k^-)\frac{T'}{N} < 1.$$

For correcting larger sampling frequency errors, two sub-sets S_p^+ and S_p^- closer to the center of the frame may be used, or two sub-sets C_p^+ and C_p^- to have smaller phase variations.

The detector for detecting sampling frequency errors accelerates the speed of the synchronization with a low complexity addition. The residual sampling frequency deviation depends on the loop filter used for synchronizing the sampling frequency and the noise level.

CLAIMS:

1. A digital transmission system comprising a transmitter (11, 13, 15) of multicarrier signals transmitted in frames, a part of the multicarriers transmitting pilot signals which are distributed in the frame in a pre-established order, and a receiver (111, 113, 115) comprising:

- sampling means (30, 35) for sampling the received baseband-converted multicarrier signals with a sample clock (H_s),

- and synchronization means (32, 33, 34) for synchronizing the sample clock, characterized in that the synchronization means comprise a frequency detector (33) which corrects frequency deviations of the sample clock by calculating a first average phase variation for the pilot signals appearing on the high-frequency carriers, and a second average phase variation for the pilot signals appearing on the low-frequency carriers, said frequency deviations being corrected in proportion to a difference of average phase variations which separates the first average phase variation from the second average phase variation in relation to a frequency gap separating the high frequencies from the low frequencies.

2. A receiver (111, 113, 115) for receiving multicarrier signals transmitted in frames, one part of the multicarriers transmitting pilot signals which are distributed in the frame in a pre-established order, the receiver comprising:

- sampling means (30, 35) for sampling the received baseband-converted multicarrier signals with a sample clock (H_s),

- and synchronization means (32, 33, 34) for synchronizing the sample clock, characterized in that the synchronization means comprise a frequency detector (33) which corrects frequency deviations of the sample clock by calculating a first average phase variation for the pilot signals appearing on the high-frequency carriers, and a second average phase variation for the pilot signals appearing on the low-frequency carriers, said frequency deviations being corrected in proportion to a difference of average phase variations which separates the first average phase variation from the second average phase variation in relation to a frequency gap separating the high frequencies from the low frequencies.

3. A synchronization method of synchronizing a sample clock of a receiver of digital transmissions operating with multicarrier signals transmitted in frames, a part of

the multicarriers transmitting pilot signals distributed in the frame in a pre-established order, characterized in that the method comprises the following steps:

- calculation of a first average phase variation for the pilot signals appearing on high-frequency carriers,
- calculation of a second average phase variation for the pilot signals appearing on low-frequency carriers,
- calculation of an error signal for synchronizing the sample clock, the error signal being formed by a difference of average phase variations which separates the first average phase variation from the second average phase variation in relation to a frequency gap separating the high frequencies from the low frequencies.

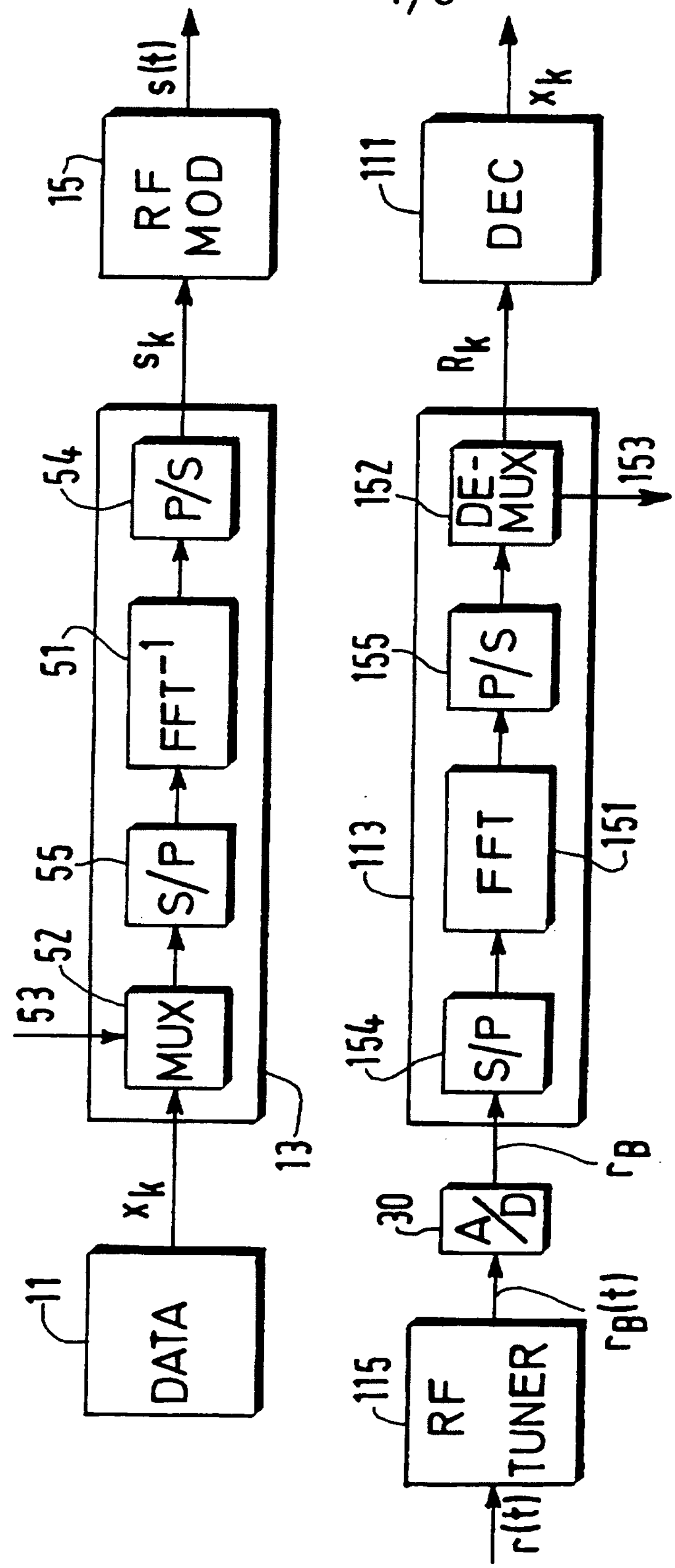
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FIG. 1

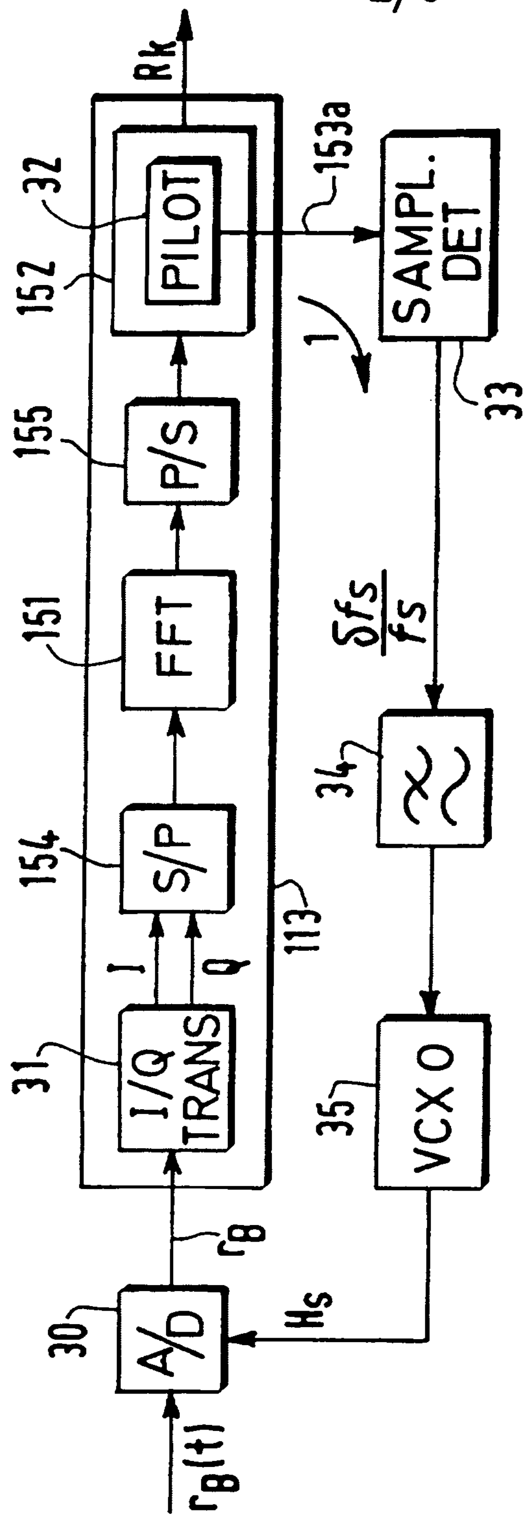
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FIG. 2

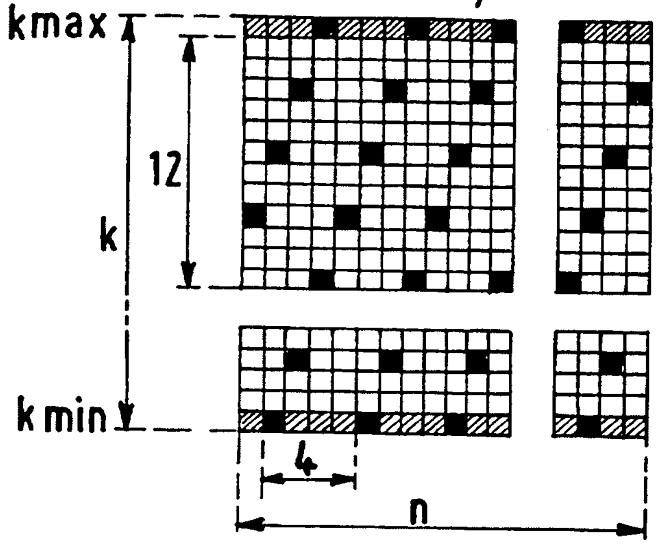

FIG. 3

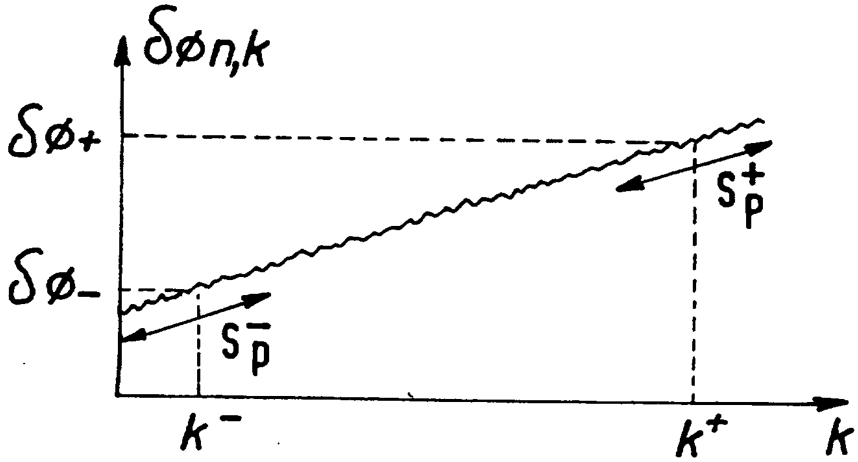

FIG. 4

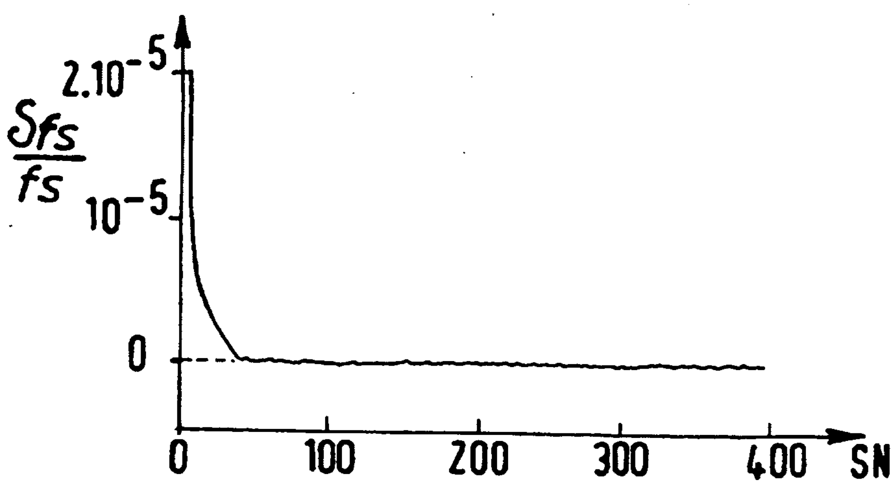

FIG. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 97/00422

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04L27/26 H04L7/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 95 19671 A (TELIA & ISAKSSON) 20 July 1995 see abstract; figures 1,2,9 see page 1, line 30 - page 2, line 5 see page 3, line 19 - line 29 see page 4, line 32 - line 38 see page 5, line 7 - line 14 see page 5, line 21 - line 25 see page 5, line 31 - line 33 see page 8, line 7 - line 12 see page 8, line 22 - line 27 see page 9, line 9 - line 11 ---	1-3

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
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